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A Renormalization Group Approach To Image Processing, A New Computational Method for 3-Dimensional Shapes in Robot Vision, and the Computational Complexity of the Cooling Algorithms.

FINAL TECHNICAL REPORT

AUTHOR

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During the period of the contract, 6/15/86-7/31/89, we have developed: I). A parallel multilevel-multiresolution algorithm for Image Processing and "low-level" Robot vision tasks, II). A Bayesian/Geometric Framework for 3-D shape estimation from 2-D images, appropriate for object recognition and other Robot tasks, III). A procedure for rotation and scale invariant representation (coding) and recognition of textures; a computationally efficient algorithm for estimating Markov Random Fields, IV). we have obtained mathematical results concerning convergence and speed of convergence of computational algorithms such as the annealing algorithm, and have studied mathematically the consistency and asymptotic normality of Maximum Likelihood Estimators for Gibbs distributions.

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FINAL TECHNICAL REPORT
ARO/SDI Contract DAAL03-86-K-0110

Principal Investigator: Basilis Gidas
Brown University

Our research supported by ARO/SDI contract DAAL03-86-K-0110, has had a number of successes in the problems of Computer (Robot) Vision and Image Processing. In particular, we have developed: I) A parallel multilevel, multiresolution algorithm for Image Processing and "low-level" Robot vision tasks, II) A Bayesian/Geometric framework for 3-D shape estimation from 2-D images, appropriate for object recognition and other Robot tasks, III) A procedure for rotation and scale invariant representation (coding) and recognition of textures; a computationally efficient algorithm for estimating Markov Random Fields, and IV) We have obtained mathematical results concerning convergence and speed of convergence of computational algorithms such as the annealing algorithms, and have studied mathematically the consistency and asymptotic normality of Maximum Likelihood estimators for Gibbs distributions.

Below we provide a brief description of the above contributions:

I) In our paper entitled "A Renormalization Group Approach to Image Processing Problems", IEEE PAMI-11(1989) 164-180 (attached to this report); we have introduced a multiresolution, multilevel procedure for studying Image processing (segmentation, noise removing, texture and motion analysis, etc.), and Computer Vision tasks. The method combines Renormalization Group Ideas, Monte-Carlo type algorithms, and is implementable on parallel architectures. The algorithm should be useful in other problems such as tracking military objects, analysis of satellite data, and speech recognition. The method has been tested in many experiments, and the results have been remarkable.

II) The real-time acquisition of reliable and complete 3-D features from 2-D images, is a key step to object recognition and Robot manipulation tasks. It has been the central point in our studies of 3-D Vision. In a paper entitled "A Bayesian/Geometric Framework for Reconstruction of 3-D Shapes for Robot Vision", High Speed Computing II, SPIE Vol. 1058 (1989) 86-93 (and in Ph.D. Thesis by my student José Torreão, 1989), we have developed and experimentally tested a Bayesian framework for examining 3-D features from two noisy images acquired by a single camera, but with two light sources of different origins. The key to this method is appropriate prior distributions which describe *Random Surfaces*. These distributions (inspired by Statistical Mechanics models) quantify our intuitive expectations about 3-D shapes, but do not make any particular assumptions about the surfaces (i.e. whether they are planar, spherical, quatric, etc.). The method has provided an efficient and accurate solution to some traditional problems of Shape-from-Shading, Shape-from-Texture, and partial classification of zero-crossings. The framework is suitable for sensor fusion (e.g. laser radar data, infrared data, and visible light data).

III) Rotations and scale invariant recognition of objects is one of the unresolved and important problems in Robot vision. Our multiresolution, multilevel method (part I) aims at this problem. Furthermore, in a recent paper (attached in this report) entitled "A Variational Method for Estimating the Parameters of MRF from Complete or Incomplete Data" (and in Ph.D. Thesis by my student Murilo Almeida, (1989), we have introduced a procedure for studying representation (coding) and recognition of textures in a scale and orientation invariant way. The procedure is based on a class of models which are defined at all levels of resolution and scale. These models contain a number of parameters which need to be estimated from the data ("learning" stage). This motivated us to develop a fast algorithm (the *Variational Method*) for estimating these parameters. The algorithm is more efficient than, and as accurate as, its best competitors: the Maximum Pseudo-Likelihood method, and the EM algorithm. The algorithm is general and suitable for Neural Network problems, Speech Recognition, and Tomography.

IV) The problems of Image Processing and Computer Vision have led to a number of interesting mathematical questions concerning the theoretical behavior of computational and inference algorithms. In the past, we have studied convergence and speed of convergence for the annealing and Langeving algorithms. We have also proven that our multiresolution algorithm (the Renormalization Group algorithm) converges to the true solution, and have analyzed its computational complexity. More recently (past two years), in a series of papers (some of which are attached to this report), we have settled in a satisfactory way the consistency and asymptotic behavior (as the size of the problems become larger and larger, of Maximum Likelihood estimations for Gibbs distributions. These studies involve Large Deviation techniques, and have given rise to an interesting interplay between Statistics and the phenomena of Phase Transitions in Statistical Mechanics.

Recent Publications

"Consistency of Maximum Likelihood and Pseudo-Likelihood Estimators for Gibbs Distributions", in Stochastic Differential Systems, Stochastic Control Theory, and Applications, IMA Vol. 10, Springer-Verlag (1986), 129-145, ed: W. Fleming and P.L. Lions.

"Simulations and Global Optimization," in Random Media, IMA Volumes in Mathematics and Its Applications Vol. 7 (1987) pp. 129-145, ed: G. Papanicolaou.

"A Hierarchical Multiscale Processing of Images", Transactions of the Fourth Army Conference on Applied Mathemtics and Computing (1987) 215-225.

"Parameter Estimation for Gibbs Distributions, I: Fully Observed Date", submitted to Annals of Statistics (1988).

"Parameter Estimation for Gibbs Distributions from Partially Observed Data", submitted to Prob. Th. and Rel. Fields (1988) (with F. Comets).

"Asymptotics of Maximum Likelihood Estimators for the Curie-Weiss Model", submitted to Ann. Stat. (1988) (with F. Comets).

"A Multilevel-Multiresolution Technique for Computer Vision via Renormalization Group Ideas", Proceedings on Optoelectronics and Laser Applications in Science and Engineering, SPIE, January 1988, 214-218, ed: D. P. Casusent.

"A Renormalization Group Approach to Image Processing Problems", IEEE Transactions, PAMI, Vol. 11, No. 2 (1989) 164-180.

"A Bayesian Framework for the Estimation of 3-D Shapes in Robot Vision" (with J. Torreae) High Speed Computing II, International Society for Optical Engineering, to be appear January 1989.

"The Multi-Grid Method and a Two-Stage EM Algorithm for Emission Tomography" (with M. Hudson), to be submitted to IEEE Trans. Medic. Images (January 1989).

"Boundary Finding and Reconstruction of 3-D Surfaces from Two Images with Noise", in preparation.

"3-D Shape Reconstruction for Robot Vision from Texture", in preparation.

"Efficient Parameter Estimation Methods for Gibbs Distributions" (with M. Almeida), in preparation.

"Consistency and Asymptotic Normality of ML and Variational Estimators for Markov Random Fields with Continuous State Space", in preparation.

INVITED PAPERS

"Statistical Inference for Markov Random Fields and Appliations to Computer Vision", Journal of Applied Statistics (Special issue on Statistical Methods in Digital Image Processing, to apear 1989).

"Fast Parallel Algorithms for Global Optimization", Journal of Algorithmica (paper invited by Professor A. Sangiovani-Vincentelli, University of California at Berkeley, 1989).

Ph.D. Theses (Titles and Abstracts attached)

1. Steven H. Adachi: "Convergence to Equilibrium and Critical Slowing Down of Dynamical Models in Statistical Mechanics", May 1987.

2. Murilo P. de Almeida: "Statistical Inference for MRF with Unbounded Continuous Spins and Applications to Texture Representation", May 1989.

3. José Torreão: "A Bayesian Approach to 3-D Shape Estimation for Robotic Vision", defended September 1989.

CONFERENCES 1988/89 (Invited Lectures)

"A Multilevel-Multiresolution Technique for Image Analysis and Robot Vision via Renormalization Group Ideas", 20th Symposium on Interface: Computing Science and Statistics, April 20-23, 1988, Acton, Virginia.

"Efficient Methods for Parameter Estimation of Markov Random Fields", Innovative Science and Technology Office's Annual Information Processing Symposium, June 20-24, 1988, Arlington, Virginia.

"Texture Identification and Parameter Estimation of Gibbs Distributions", Institute for Mathematics and its Applications, University of Minnesota, Minneapolis, Minn. August 1-5, 1988.

"A Multiresolution Method for Robotics and Computer Vision Tasks", Symposium on Probability and its Applications, August 16-19, 1988, Fort Collins, Colorado.

"Global Optimization with Constraints and Applications to Robot Vision", High Speed Computing II, SPIE - The International Society for Optical Engineering, January 15-20, 1989, Los Angeles, California.

"Fast Parallel Algorithms and Computer Experiments for 3-D Vision Problems", Conference/Workshop on Sensor Signal Processing, April 25-27, 1989, Xerox Center, Leesburgh, Virginia.

Seventh Army Conference on Applied Mathematics and Computing (Special Session: Stochastic Methods for Image Analysis), June 6-9, 1989, U.S. Military Academy, West Point, N.Y. (Title of talk to be decided).

"Asymptotic Properties of Maximum Likelihood Estimators from Noisy Data for Gibbs Distributions", Durham Research Symposium, London Mathematical Society, July 21-31, 1989, Durham, England.

Conference on "Statistics, Earth and Space Sciences", The Bernoulli Society, August 21-25, 1989, Leuven, Belgium (Title of talk to be decided).

COLLOQUIA LECTURES (1988/89)

Tufts University, Department of Computer Science, Medford, MA., April 1988.

Harvard University, Division of Applied Sciences, Cambridge, MA., May 1988.

New York University, Courant Institute for Mathematical Sciences, New York, N.Y., November 1988.

Swarthmore College, Department of Physics and Astronomy, Swarthmore, PA., January 1989.

Columbia University, Department of Statistics, New York, N.Y., February 1989.

State University of New York at Stony Brook, Department of Applied Mathematics and Statistics, Stony Brook, N.Y. (tentatively arranged for May 1989).